



Measurement of the parity violating asymmetry A_γ in $\vec{n} + p \rightarrow d + \gamma$

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Abstract

The weak interaction between neutrons and protons has never been resolved experimentally. In analogy with the strong NN interaction, the weak NN interaction at low energy can be parametrized in terms of a meson exchange model with parity violating meson–nucleon couplings. Unlike the measured proton–proton weak interaction, the neutron–proton weak interaction is sensitive to the weak pion–nucleon coupling constant H_π^1 . This coupling, which is responsible for the longest-ranged part of the weak NN interaction and is therefore an essential part of any description of weak interactions in nuclei, remains undetermined despite many years of effort. A measurement of the gamma ray directional asymmetry A_γ in the capture of polarized neutrons by parahydrogen has been proposed at Los Alamos National Laboratory. The goal of this experiment is to determine A_γ with a relative standard uncertainty of $< 5 \times 10^{-9}$, which is smaller than all modern predictions for the size of the asymmetry. The design of the experiment is presented, with an emphasis on the techniques used for controlling systematic errors. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The weak interaction between nucleons is worth understanding for a number of reasons. If one assumes the electroweak theory is correct, a study of the weak nucleon–nucleon (NN) interaction has the potential to improve our understanding of the strongly interacting limit of quantum chromodynamics (QCD), which is clearly a problem of fundamental importance. Like the electromagnetic interaction, the weak interaction between quarks and leptons is understood at the fundamental level and is weak enough to probe strongly interacting systems without affecting the strong dynamics. The potential for surprises is illustrated by the example of the $\Delta I = \frac{1}{2}$ rule in strangeness-changing nonleptonic weak processes. Strong interaction effects appear to boost $\Delta I = \frac{1}{2}$ nonleptonic weak amplitudes relative to the $\Delta I = \frac{3}{2}$ channel despite the fact that these amplitudes are comparable in the perturbative QCD limit. Perhaps similar QCD-induced effects will be seen in the strangeness-conserving sector.

The NN weak interaction is also the only practical way to study quark–quark neutral currents at low energy. The neutral weak current conserves quark flavor to high accuracy in the standard electroweak model (due to the GIM mechanism). Therefore it is not seen at all in the well-studied strangeness-changing nonleptonic weak decays. We therefore know nothing experimentally about how QCD modifies weak neutral currents. In fact, the effects of quark–quark neutral currents have been seen only recently in collider experiments [1–5].

There are also applications in other fields. Starting from a knowledge of the NN weak interaction one could use the large existing body of experimental information on parity violation in nuclei to address important issues in nuclear physics. Here is the most recent example: measurements of parity violation in atoms have recently been seen for the first time due to the NN weak interaction through the observation of the nuclear anapole moment in ^{133}Cs [6]. The nuclear anapole moment is a new ground-state property of nuclei which, like the magnetic moment of a nucleus, can be calculated in a relatively model-independent manner.

In order to use measurements of anapole moments to probe nuclear structure, however, the weak NN interaction itself must be understood.

Unfortunately, the rate of progress in our understanding of the NN weak interaction has been slow despite strong experimental activity. Two reviews of the subject conducted a decade apart [7,8] reach essentially the same conclusion: the weak NN couplings are unknown. The reasons for the slow advance are both theoretical and experimental. The experimental problems stem from the small size of weak amplitudes relative to strong amplitudes (typically $\approx 10^{-7}$ at low energies). The theoretical difficulties are encountered in trying to relate the underlying electroweak currents to low-energy observables in the strongly interacting regime of QCD. One expects the strong repulsion in the NN interaction to keep the nucleons too far apart for a simple direct exchange of W and Z bosons between quarks in different nucleons to represent an accurate dynamical mechanism.

The current approach is to split the problem into two parts. The first step is to map QCD to an effective theory expressed in terms of the important degrees of freedom of low-energy QCD, mesons and nucleons. In this process, the effects of quark–quark weak currents appear as parity-violating meson–nucleon couplings [9]. A meson exchange model is known to work well as a low-energy description of the strong interaction [10]. Even if it is not an honest representation of the NN interaction at the quark level, it at least is a convenient way of encoding the amplitudes. The second step is to use this effective theory to calculate electro-weak effects in the NN interaction and to determine the weak couplings from experiment. If the values of the couplings inferred from different experiments are consistent, we can use the results with confidence to improve our understanding of nuclear parity violation. For this application, the parity violating coupling of the pion is important to understand, since it produces the longest-range effect. If the meson exchange model fails, then we have learned something interesting about the strongly interacting limit of QCD which would demand explanation.

Despite the QCD-induced complexity, there is one simple expectation from the standard

electroweak model which might survive. A naive analysis of the structure of the quark–quark weak current implies that the isovector part of the effective weak Hamiltonian should be strongly dominated by the neutral current contribution. This happens because the charged current contribution to the $\Delta I = 1$ effective Hamiltonian comes only from a $(u \rightarrow s) \times (s \rightarrow u)$ transition, which is suppressed by a factor of approximately $V_{us}^2 = 0.04$ relative to the neutral current contribution to $\Delta I = 1$. In terms of the meson exchange picture of the weak NN interaction, this means that weak pion exchange is particularly interesting, since it should be dominated by quark–quark neutral currents about which nothing is known experimentally at low energy. It is also the longest range component of the weak NN interaction, and therefore presumably the most reliably calculable in its effects in the NN system. For all of these reasons, the coupling constant for weak π exchange, H_π^1 , is of special interest.

Yet another perspective on the significance of the study of $\Delta I = 1$ parity violation in the NN system can be gained by viewing how this interaction changes in certain limits. For example, in the limit of a diagonal KM matrix (i.e., no mixing of quarks of different generations), a vanishing weak mixing angle, and degenerate quark masses in each generation, all NN parity violation must be $\Delta I = 0$. If one allows for the large mass splitting between the strange and charmed quark but keeps a diagonal KM matrix and zero weak mixing angle, one concludes that all $\Delta I = 1$ parity violation in this limit would come from the effects of strange quarks in the nucleon [11]. Since both the weak mixing angle and the KM angles are small in the real world one expects strange quarks to be important in $\Delta I = 1$ parity violation and therefore in H_π^1 .

Indeed this expectation is borne out in some recent calculations of H_π^1 in various models. The quark model-based calculation of Desplanques, Donoghue, and Holstein (DDH) [9] and a recent update [12] showed that strange quark contributions to H_π^1 were important. Recent calculations in Skyrme models show this effect explicitly: the two-flavor calculation gives a value for H_π^1 which is nearly an order of magnitude smaller than the result for three flavors [13]. This confirms an earlier estimate made with chiral lagrangians [14].

Predictions for the value of H_π^1 from DDH, the Skyrme model, and a recently corrected QCD sum rule calculation [15] all range from 1.5 to 3.0×10^{-7} .

The size of H_π^1 is not known. The most reliable information on the size of H_π^1 is believed to come from measurements of the circular polarization of 1081 keV gamma rays from ^{18}F [7]. The current results have been interpreted as an upper limit $H_\pi^1 \leq 1.3 \times 10^{-7}$. One theoretical calculation extracts from the ^{133}Cs nuclear anapole moment measurement a value $H_\pi^1 = 9.5 \pm 2.1(\text{expt.}) \pm 3.5(\text{theory}) \times 10^{-7}$ [16], which is significantly larger than the ^{18}F value. However, there are nuclear structure uncertainties involved and it is too soon to draw a firm conclusion [17].

A measurement in the nucleon–nucleon system sensitive to H_π^1 is needed to determine its value beyond a reasonable doubt. The system must be simple enough that calculations which can connect experimental observables to weak couplings can be performed reliably. In practice, this means that one must perform experiments in light nuclear systems ($p, d, {}^3\text{He}, {}^4\text{He}$). Measurements of parity violation have been performed in pp scattering. In this case, however, identical particle constraints forbid a contribution from weak charged pion exchange to first order, and weak neutral pion exchange is suppressed because it violates CP invariance (Barton's theorem). Therefore, pp parity violation is completely insensitive to H_π^1 .

In the case of the np system, an analysis of the available low-energy channels shows that parity violation in the reaction $\bar{n} + p \rightarrow d + \gamma$ is almost entirely due to weak pion exchange. In particular, the relation between the PNC gamma ray asymmetry A_γ and H_π^1 is calculated to be [18–21]

$$A_\gamma = -0.045(H_\pi^1 - 0.02H_\rho^1 + 0.02H_\omega^1 + 0.04H_\pi^{1'}) \quad (1)$$

The final result from the last experiment to search for the PV asymmetry in $\bar{n} + p \rightarrow d + \gamma$ was $A_\gamma = -1.5 \pm 4.7 \times 10^{-8}$ [22]. This result is in mild conflict with one of the H_π^1 estimates from the anapole moment measurement, but it is not sensitive enough to reach the range of values for H_π^1 predicted by theory. We propose to measure

A_γ to a precision of 5×10^{-9} [23]. At a minimum, such a result will clearly distinguish between the ^{18}F and ^{133}Cs values for H_π^1 . In addition, there is also a strong possibility that a non-zero result will be seen and that the value of H_π^1 will finally be known.

2. Experimental design

In this section we describe the conceptual design for the proposed measurement of A_γ in $\bar{n} + p \rightarrow d + \gamma$. The apparatus, shown schematically in Fig. 1, consists of a cold neutron source, followed by a neutron polarizer, and a liquid parahydrogen target, surrounded by an array of gamma detectors and with a current-mode neutron monitor downstream. Neutrons from the spallation source are moderated by a liquid hydrogen moderator. The source is pulsed, thus allowing measurement of neutron energy through time-of-flight techniques. The neutron guide transports the neutrons from the moderator through the biological shield with high efficiency. The neutrons are then polarized vertically by transmission through polarized ^3He gas. The neutron spin direction can be

subsequently reversed by a radio-frequency resonance spin rotator. This device consists of a RF cavity in a uniform magnetic field which acts on a well-defined length of the beam. With proper choices of the frequency and amplitude of the RF field, the spins of neutrons in one velocity class will be flipped. With proper phasing of the magnitude of the RF field as a function of time with respect to the pulsed proton beam, the condition for flipping the neutron spin can be satisfied for all of the velocity classes in the pulsed neutron beam as they arrive at the cavity. The use of this type of a spin flipper (which does not require a static magnetic field gradient unlike the RF flippers used at CW reactor sources) reduces the systematic error associated with the $\mu_n \cdot \nabla B$ force, where μ_n is the neutron magnetic moment. In addition, the energy absorbed by the neutron from the RF field is converted into a change in potential energy of the neutron in the static magnetic field: thus the kinetic energy of the neutron remains the same. Therefore the neutron energy spectrum after the flipper is independent of the neutron spin direction. The neutrons are captured in the target, which consists of liquid parahydrogen. This state of hydrogen is required, since neutrons depolarize quickly in the

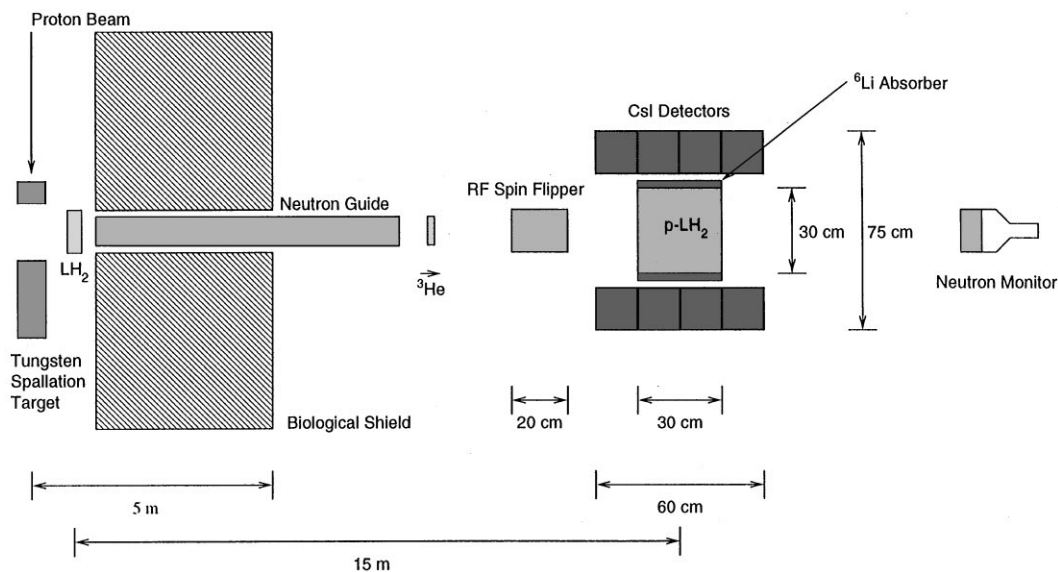


Fig. 1. The conceptual design for the proposed experiment, showing the most important elements (not to scale). Approximate sizes and distances are indicated for some features.

$J = 1$ orthohydrogen through spin-flip scattering, while those with energies below the ortho-para ground state energy difference of 15 meV retain their polarization in the $J = L = S = 0$ parahydrogen. Gammas emitted in the capture process are detected in the CsI(Tl) detectors surrounding the target, which are viewed by vacuum photodiodes operating in current mode. The current-mode beam monitor can take a snapshot of the neutron energy distribution on a pulse-by-pulse basis and will be used to measure the orthohydrogen concentration in the target.

The parity-violating asymmetry causes an up-down asymmetry in the angular distribution of the gamma rays for vertical neutron spin. When the neutron spin is reversed, the up-down gamma asymmetry reverses. The parity-violating asymmetry in gamma flux,

$$\frac{d\omega}{d\Omega} = \frac{1}{4\pi}(1 + A_\gamma \cos \theta_{s,\gamma}) \quad (2)$$

is a measure of H_π^1 , as discussed in the introduction.

3. Systematic errors

We distinguish between statistical and systematic errors. The experiment is designed to measure the directional asymmetry of the emission of gamma rays with respect to the neutron spin direction. A source of systematic error produces a signal in the detector that is coherent with the state of the neutron spin. The size of statistical errors is important to establish when discussing systematic errors, because it is important to be able to diagnose systematic errors in a time that is short compared to the time it takes to measure the directional γ asymmetry. Systematic errors can be further classified according to whether they are instrumental in origin or arise from an interaction of the neutron spin other than the directional γ asymmetry in the $\bar{n} + p \rightarrow d + \gamma$ reaction. Finally, it is important to isolate, amplify, and study experimentally potential sources of systematic errors.

It is not possible to give a complete list of sources of instrumental systematic errors. It is essential to be able to tell whether such effects are present in

a short time. These effects are not associated with the neutron beam. There are two types of instrumental asymmetries; additive couplings and gain shifts. Additive couplings will be diagnosed by running the experiment with the beam off and looking for a nonzero up-down asymmetry. The electronic noise is $\frac{1}{100}$ of counting statistics. In the presence of electronic noise only, achieving an accuracy of 0.1×10^{-8} (the statistical error in A_γ will be 0.5×10^{-8} in one year of data) will require a running time $5^2/100^2$ of 1 yr, ≈ 1 day.

In order to search for gain shifts we will illuminate the detectors with light from light-emitting diodes. The level of illumination will produce a photo-cathode current 10 times larger than that due to neutron capture, where we expect the number of photo-electrons per 2.2 MeV gamma from CsI(Tl) will be ≈ 500 . The time to measure a gain shift of 0.1×10^{-8} will be $5^2/(10 \times 1000)$ of 1 yr ≈ 1 day.

The most important experimental tool we have to isolate a parity violating signal in this experiment is the neutron spin flip. It is therefore absolutely essential that the process of flipping the neutron spin have a negligible effect on all other properties of the apparatus.

One method of spin reversal consists of reversing the polarization direction of the ^3He target. The ^3He spin can be reversed by an adiabatic fast passage or adiabatic reversal of the magnetic holding/guide field. The magnetic field (at the polarizer the fully polarized ^3He nuclei create a field of about 2 Gauss) due to the reversed magnetic moments of the polarized ^3He nuclei in the neutron polarizer causes a change in the static magnetic field at the location of the gamma detectors. This change is about 1×10^{-6} gauss. Coupled with the measured change in the gamma detector efficiency $2 \times 10^{-5}/\text{gauss}$, this gives a negligible efficiency change of 2×10^{-11} .

Another method of neutron spin reversal is performed by turning on and off the ≈ 30 kHz RF magnetic field in the spin flipper. This field, although closer to the detectors than the ^3He cell, can be shielded very effectively because the skin depth of the 30 kHz RF field in aluminum is 0.5 mm. In addition, the intrinsic detector efficiency should be less sensitive to an RF field than a DC field. Care

Table 1

A list of systematic effects in the proposed $\bar{n} + p \rightarrow d + \gamma$ parity violation experiment. We list the reaction, the associated correlation, the intensity pattern it gives rise to in the gamma detectors (U-D is along the neutron polarization and L-R is orthogonal to it), the dependence on the neutron time-of-flight (TOF) at a pulsed neutron source, the estimated size of the effect, and whether or not the effect vanishes for neutrons with energies above 15 meV (which is the threshold for neutron depolarization in liquid parahydrogen)

Reaction	Correlation	Pattern	TOF	Size	Zero above 15 meV?
$\bar{n} + p \rightarrow d + \gamma$	$\vec{s}_n \cdot \vec{k}_\gamma$	U-D	t^0	5×10^{-9}	Y
$\bar{n} + p \rightarrow \bar{n} + p$	$\vec{k}_n \cdot \vec{s}_n \times \vec{k}_n$	L-R	t^{-1}	2×10^{-10}	Y
$\bar{n} + p \rightarrow d + \gamma$	$\vec{k}_\gamma \cdot \vec{s}_n \times \vec{k}_n$	L-R	t^{-2}	2×10^{-11}	Y
$\bar{n} + p \rightarrow d + \gamma$	$\vec{s}_\gamma \cdot \vec{s}_n$	U-D	t^0	1×10^{-10}	Y
$\bar{n} \rightarrow p + e^- + \bar{\nu}_e$	$\vec{s}_n \cdot \vec{k}_e$	U-D	t^0	3×10^{-11}	Y
$\bar{n} + d \rightarrow t + \gamma$	$\vec{s}_n \cdot \vec{k}_\gamma$	U-D	t^0	1×10^{-10}	Y
$\bar{n} + p \rightarrow \bar{n} + p$	$\vec{k}_n \cdot \vec{s}_n \times \vec{k}_n$	L-R	$t^{-2.8}$	1×10^{-10}	Y
$\bar{n} + {}^6\text{Li} \rightarrow \alpha + t$	$\vec{s}_n \cdot \vec{k}_n$	U-D	t^0	2×10^{-11}	Y
$(\vec{\mu}_n \cdot \vec{\nabla})\vec{B}$	$(\vec{s}_n \cdot \vec{\nabla})\vec{B}$	U-D	t^1	1×10^{-10}	N
$\bar{n} + A \rightarrow \bar{A} + 1$	$\vec{s}_n \cdot \vec{k}_e$	U-D	Varies	$< 10^{-10}$	N
$A + 1 + e^- + \bar{\nu}_e$					

must be taken to ensure that there is no spurious electronic pickup induced by the RF switching. We intend to forestall this problem by switching the RF power into a dummy coil when the neutron spin is not being flipped (the effectiveness of this strategy will be verified by off-line testing).

We will reverse the neutron spin on a pulse-by-pulse basis (the 20 Hz time scale set by the LANSCE source) using the RF spin flipper with a $+-+--++-$ pattern. This pattern eliminates the effects of first- and second-order time-dependent drifts in detector efficiencies. The neutron spin will be reversed every few hours by reversing the polarization direction of the ${}^3\text{He}$ polarizer. Finally, we will reverse the direction of the holding/guide field every few hours. Instrumental effects arising from the state of the RF spin flipper, the ${}^3\text{He}$ cell, the holding/guide field, or from other parts of the apparatus will have different dependences on the different reversals. These different dependences can be used to identify the source of potential instrumental systematic errors. Any instrumental or spin-dependent systematic error that depends on the ${}^3\text{He}$ state, the spin flipper state, or the holding field state can be reduced by averaging over different reversal methods.

Finally, we consider systematic errors arising from interactions of the polarized neutron beam itself. This type of false effect is potentially the most difficult to eliminate. Fortunately, these effects are

all small, $\ll 10^{-8}$, as can be seen in Table 1. This is ultimately due to the small size of spin-dependent parity conserving asymmetries from p-wave scattering amplitudes ($kR \leq 10^{-5}$) and the symmetry of the detector array ($\approx 10^{-2}$). In order to produce a false asymmetry, an interaction must occur after the spin is reversed by the RF spin flipper, otherwise the effect of the interaction would be averaged out by the eight-step reversal sequence. The interaction must involve a correlation of the neutron spin vector and a quantity from the final state that deposits energy in the gamma detector. We have identified all possible Cartesian invariants that satisfy these conditions and evaluated the associated false asymmetries. Different potential sources of false asymmetry produce effects that depend on time of flight (neutron energy) in a characteristic fashion. For example, the $\bar{n} + p \rightarrow d + \gamma$ directional asymmetry, A_γ , produces an up-down pattern (for neutron spin up-down) that is independent of neutron energy up to an energy of 15 meV. Above 15 meV, the neutrons depolarize in the parahydrogen and the asymmetry vanishes.

4. Summary

We are proposing an experiment to measure A_γ with a statistical precision of $A_\gamma \sim 5 \times 10^{-9}$, and with negligible systematic error [23]. This

measurement can determine the weak pion-nucleon coupling H_π^1 , independent of nuclear structure assumptions. It would represent the first measurement of a weak meson-nucleon coupling. This is an essential step in understanding both weak interactions in nuclei and modifications of the quark-quark weak interaction in the strongly interacting regime of QCD.

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